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THE FREE ATMOSPHERE IN THE VICINITY OF FRONTS

Analysis of the observations by the Meteorological Research Flight, 1950-52

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THE FREE ATMOSPHERE IN THE VICINITY OF FRONTS

Analysis of the observations by the Meteorological Research Flight, 1950-52

SUMMARY

During the period 1950 to 1952 some 20 flights were made by aircraft of the Meteorological Research Flight from Farnborough in order to explore the structure of fronts. The results indicate the great complexity of the atmosphere in frontal regions. Although the observations confirm that a sloping baroclinic zone exists, it is clear that no idealized frontal model can adequately represent an individual front. Small-scale irregularities of temperature are sufficient to prevent any clear delimitation of the frontal zone.

Some very dry air was often found in frontal regions in close juxtaposition to cloud and rain. Its presence can be adequately explained by large-scale air movements which are primarily horizontal. Cloud structure and turbulence in frontal regions were also observed.

§ 1—INTRODUCTION

During the period November 1950 to July 1952 a series of flights was made by the Meteorological Research Flight, the purpose of which was to study the detailed structure of the atmosphere in the neighbourhood of fronts. Twenty-three such flights were made during this period, and all were successfully completed with the exception of one which was cut short by engine trouble. The results of these flights are analysed in the present paper.

The general plan of each of the flights required that the aircraft should make a horizontal flight through the frontal region and return on a reciprocal track at a different level. The track was chosen to be approximately perpendicular to the front. The flight also included spiral climbs or descents at the extremities of the horizontal legs, and occasionally at other points. Meteorological observations were made at half-minute intervals throughout the horizontal legs and at vertical intervals of 500 or 1,000 ft. on the ascents and descents. The aircraft, a Hastings of the Meteorological Research Flight, operated from Farnborough following a flight plan decided on the basis of the synoptic charts constructed at the Central Forecasting Office, Dunstable. Most of the flights were made in the afternoon to facilitate comparison of the observations with the routine radio-sonde soundings at 1500 G.M.T.

It was decided at the outset that the most useful results would be obtained by exploring a variety of types of front at a variety of levels—thus some fronts were studied only in the lower troposphere and others only between 15,000 and 20,000 ft. It was hoped that the observations might bring out various common properties of all fronts; however, only in their broadest features, such as the existence of a sloping baroclinic zone and of a zone of relatively dry air.

do the individual fronts appear to be similar. In studying the results of the flights it is therefore important to remember that none of the 23 fronts which have been explored can be regarded as representative of fronts in general; neither are there sufficient fronts of any one type at a particular level (e.g. active warm fronts in the lower troposphere) to show whether any particular example can be regarded as typical of a restricted type of front. On the other hand, although some of the results are necessarily presented in statistical form, the number of fronts is too small for the sample to be statistically representative.

Operational limitations on the availability and endurance of both aircraft and crew restricted the number of fronts which could be investigated. In the early stages of the work a desire to make use of every possible occasion resulted in the inclusion of a number of very weak and inactive fronts among those investigated. It was later realized that more readily interpreted results would be obtained if flights were restricted to active fronts, and later fronts were chosen accordingly. The results of all flights are however treated together below.

§ 2—OBSERVATIONAL TECHNIQUE

So far as possible the following observations were made and recorded at half-minute intervals throughout the horizontal sections of the flights and at a vertical separation of 500 or 1,000 ft. on the climbs and descents :—

Temperature.—Temperatures were read on a flat-plate electrical thermometer mounted beneath the nose of the aircraft. The absolute accuracy of the readings of the thermometer was about $\pm$ 0·2° F., and the instrumental lag was small and unlikely to have affected the readings materially in horizontal flight. The thermometer was read to the nearest whole degree on most of the flights, but on some readings to 0·1° F. were recorded. The same correction for the airspeed of the aircraft was applied to observations in cloud and in clear air. This may have introduced some uncertainty regarding temperatures in cloud, because the air impinging on the thermometer may have been compressed under moist-adiabatic conditions instead of the dry-adiabatic conditions applying in clear air.

Frost point or dew point.—Frost points (or dew points when above 32° F.) were obtained by means of a manually operated Dobson-Brewer frost-point hygrometer. The probable error of these observations was about 1° F. at dew points and frost points from + 60° to 0° F., and 2–3° F. at frost points from 0° to —50° F. Records of frost point are not so complete as those of temperature on account of the difficulty of maintaining a long series of readings at only half-minute intervals.

Cloud.—Visual observations of the cloud above and below the aircraft were made and recorded at suitable intervals together with notes on precipitation, icing, etc.

Turbulence.—The " bumpiness " of the flight was estimated and recorded in terms of " tenths of gravity ". The degree of turbulence was recorded at half-minute intervals on most of the flights.

Height of aircraft.

§ 3—SYNOPTIC ANALYSIS OF THE OBSERVATIONS

On any one flight it was possible to explore only a small part of the frontal region. The horizontal extent of the flight, 250–300 miles, was usually sufficient to cross the most strongly baroclinic part of the frontal region, but the restriction of the investigation to two levels left a

large part of the vertical structure of the front unexplored. In order to complete the picture, and to relate the aircraft's path to the frontal zone, it was necessary to construct an atmospheric cross-section along the flight path on the basis of the routine radio-sonde and wind observations. Such a section was constructed for each of the flights. Layers of stable lapse rate relative to the air above and below were picked out from the radio-sonde observations and regarded as defining the " frontal zones " ; their boundaries were indicated on the cross-sections. Only the broad features of the soundings were used in placing the frontal zone, because it is known that small-scale irregularities of temperature render details of the soundings quite unrepresentative[1]*.

Comparison between the temperature recorded by the aircraft and temperature interpolated from the radio-sonde cross-section shows some systematic differences due to instrumental inaccuracy. On all flights except one the average difference (aircraft minus radio-sonde) was negative. The average difference increases from $-0{\cdot}8°$ F. below 5,000 ft. to $-2{\cdot}3°$ F. above 15,000 ft. Some lag is evident during climbs and descents because the difference, aircraft minus radio-sonde, averages $-0{\cdot}7°$ F. on climb, $-1{\cdot}3°$ F. on horizontal flight and $-2{\cdot}3°$ F. on descent. These discrepancies have been taken into account in analysing the data.

§ 4—THERMAL STRUCTURE OF THE FRONTAL ZONE

The general trend of temperature as given by the aircraft observations on each of the horizontal flights agrees satisfactorily with the temperature gradient shown on the corresponding cross-section as drawn from radio-sonde data alone, but there are appreciable differences in detail. Altogether the flights provided observations along 45 horizontal tracks, 30 of which passed through a frontal zone as analysed from the radio-sonde observations. The observed profiles of temperature along these 30 flight paths are reproduced in Fig. 1, and the points which have been identified as the limits of the frontal zone have been indicated. In some cases the irregularity of the temperature profile is such that an analysis into a definite frontal zone containing a strong temperature gradient separating two more or less homogeneous air masses represents a considerable idealization of the observed curve and cannot be carried out objectively ; in others the analysis in terms of a frontal zone appears simple and natural. Of the 30 horizontal flights which passed through frontal zones, 21 showed a region of concentration of the horizontal gradient of temperature in close conformity with the frontal zone which was determined from radio-sonde data. Such differences in position and intensity as occurred in these cases are little greater than would be expected from the uncertainties in the position of the aircraft and the differences in time between the observations. On the remaining 9 horizontal flights it was difficult to identify the frontal zone satisfactorily.

The most clearly defined frontal zones were found in the upper troposphere in association with cold fronts. The striking example of November 3, 1950, for which profiles at 550 and 485 mb. are included in Fig. 1, was obtained on the first flight of the series. The weather situation is illustrated by the synoptic charts and cross-section in Fig. 2.

An example of the absence of a clearly defined frontal zone is given by the flight of March 19, 1952 which investigated an active warm front off the west of the United Kingdom. At the lower flight level (860 mb.) temperature increased irregularly toward the warm front throughout the flight. At the upper flight level (710 mb.) the main temperature gradient appears to be above the surface warm front (see Fig. 1), but this is difficult to reconcile with the radio-sonde observations which indicate the main temperature contrast farther east ; it also implies a baroclinic zone inclined towards the warm air. The synoptic situation is illustrated in Fig. 3 together with an atmospheric cross-section along the flight path.

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* The index numbers refer to the bibliography on p. 23.

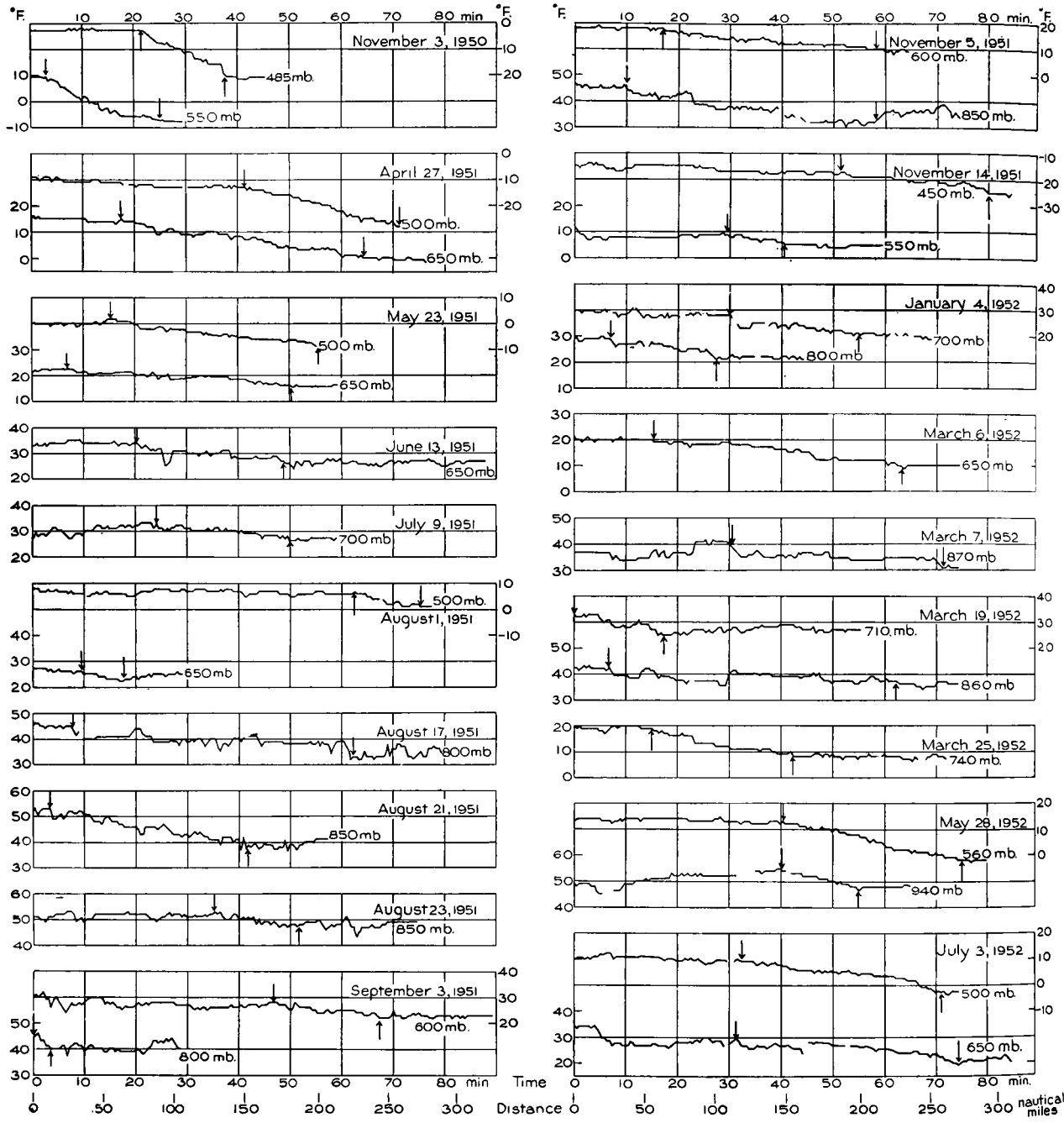


FIG. 1—PROFILES OF TEMPERATURE OBSERVED BY AIRCRAFT ON HORIZONTAL FLIGHT THROUGH FRONTAL ZONES

All profiles are arranged with the warm air mass to the left. The boundaries of the frontal zones as used in the analysis of data are indicated by arrows

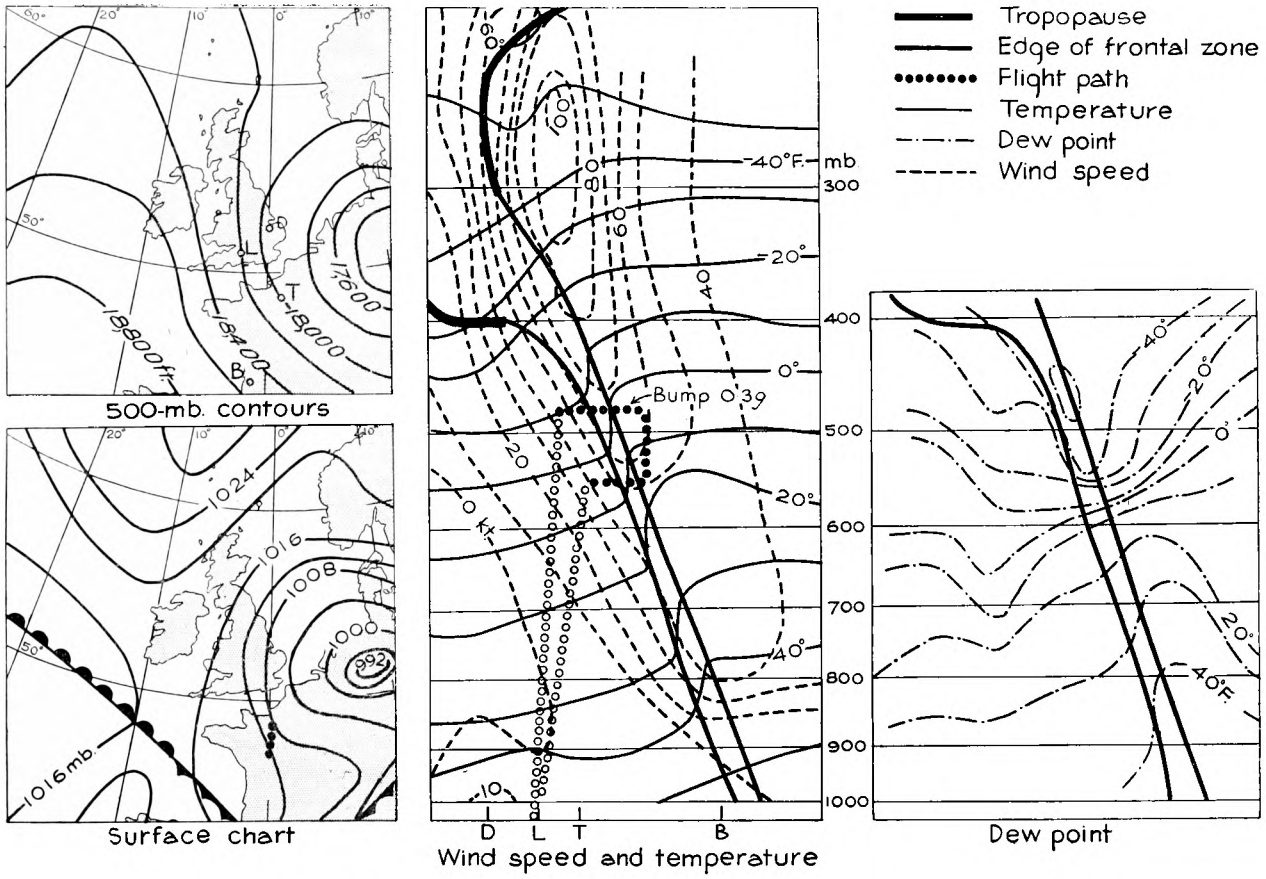


FIG. 2—SYNOPTIC SITUATION AND CROSS-SECTIONS AT 1500 G.M.T., NOVEMBER 3, 1950
D = Downham Market, L = Larkhill, T = Trappes, B = Bordeaux

In order to present some information on the width of the frontal zones and the temperature change across them, the histograms in Fig. 4 have been constructed. The limits of the frontal zones have been identified on the horizontal temperature profiles as indicated in Fig. 1. For comparison the radio-sonde cross-section has been used to make an estimate of the overall change in temperature between the two air masses, and the distance over which a significant temperature gradient extended. This may be called the " frontal region " and histograms concerning its width and temperature contrast are given in the lower diagrams of Fig. 4 for those same occasions and levels for which flights through the frontal zones were made.

The average width of the " frontal region " was about 600 miles and the average temperature difference across it about 15°F. The horizontal flights show frontal zones with an average width of about 130 miles, that is about a quarter of the total width of the frontal region, and a temperature difference of 9°F., a little more than half the total air-mass contrast. The variation from front to front and the uncertainties of the identification of the frontal boundaries are such that these figures can be little more than a broad indication of the usual structure of a frontal zone, but it is fairly clear that in the free atmosphere zones less than 50 miles in width are unusual. On all the three occasions with frontal zones less than 50 miles wide the temperature contrast was small, 4°F. in two cases and 6°F. in the other ; moreover in two of the cases it is somewhat uncertain whether the aircraft completely crossed the frontal zone.

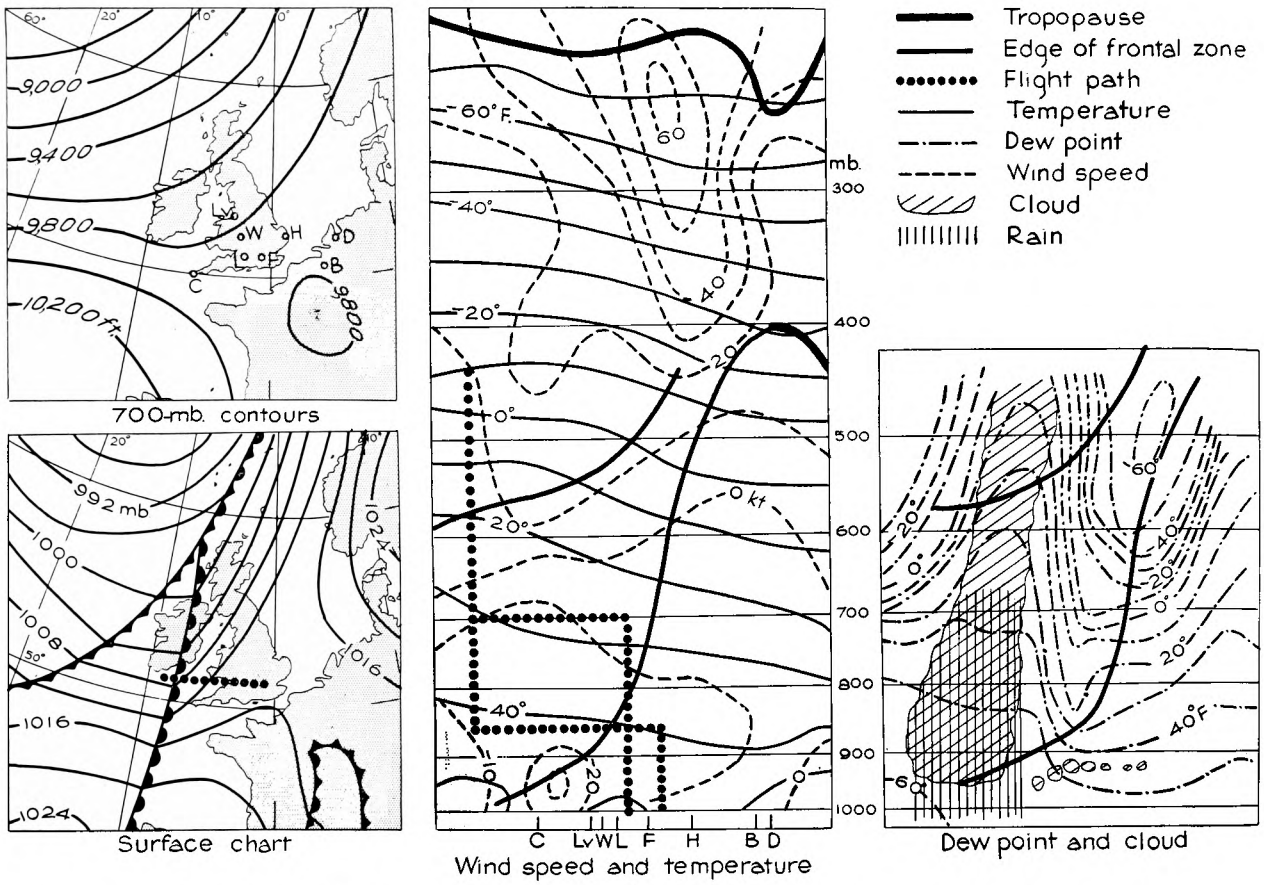


FIG. 3—SYNOPTIC SITUATION AND CROSS-SECTIONS AT 1500 G.M.T., MARCH 19, 1952

C = Camborne, Lv = Liverpool, W = Worcester, L = Larkhill,
F = Farnborough, H = Hemsby, B = Brussels, D = De Bilt

Average profiles of temperature across the fronts are given in Fig. 5 based on the aircraft observations. It might appear that the cold fronts were more clearly defined than the warm fronts, but the sample is insufficient to generalize from this data. It is not possible to obtain an entirely satisfactory profile of surface temperature to compare with the profiles of temperature observed by the aircraft. Examination of the surface synoptic charts for the occasions of the flights suggests that the gradient of surface temperature was rather less than in the free atmosphere, and was spread over a distance which also tended to be somewhat less than in the free air.

From the available data it is possible to estimate the slope of the front in three essentially independent ways :—

(i) from the heights of the limits of the frontal zone as given by the radio-sonde observations

(ii) from the ratio of the vertical thickness of the frontal zone (estimated from the radio-sonde observations) to its horizontal thickness (determined by the aircraft)

(iii) from the relative positions of the frontal zones as determined by the aircraft at the two different flight levels.

The values obtained by these three methods are given in the Appendix.

On only ten occasions could the frontal zone be identified with sufficient confidence both in the horizontal traverses at two levels and in the vertical soundings to enable all three methods to

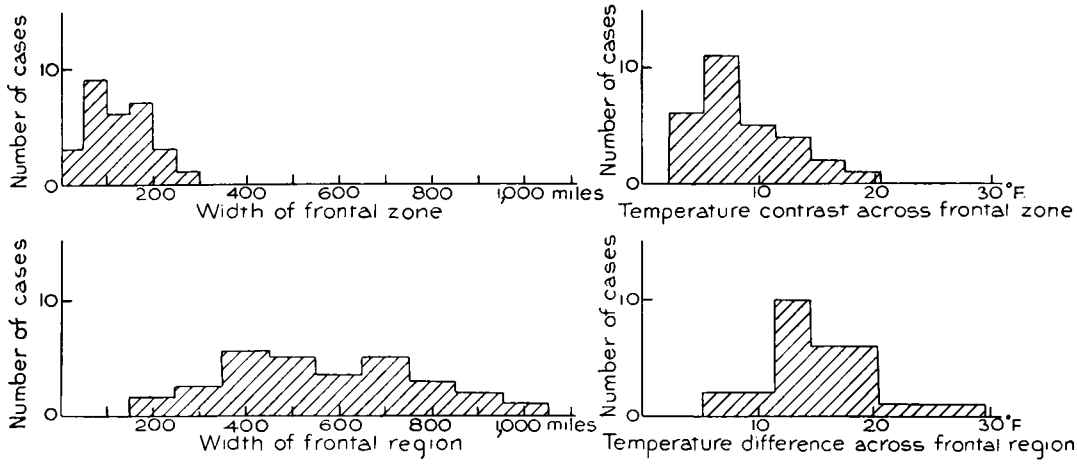
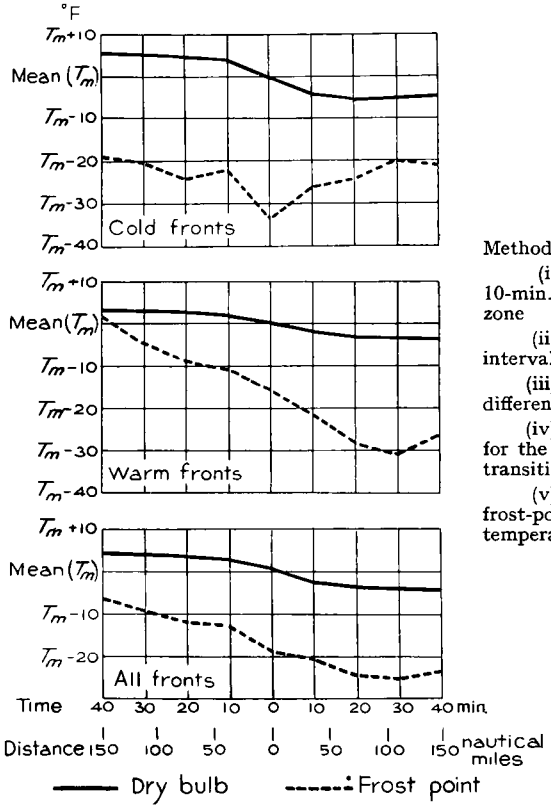


FIG. 4—HISTOGRAMS OF WIDTH OF FRONTAL ZONE AND FRONTAL REGION AND TEMPERATURE DIFFERENCE ACROSS THEM

The upper diagrams are based on the " frontal zone " as defined by the region of steepest temperature gradient on 30 horizontal temperature profiles through fronts. The lower diagrams are based on the total change of temperature from the warm to the cold air mass for the same levels as taken from the radio-sonde cross-sections



Method of forming the averages :—

(i) The average temperature and frost point was noted for periods of 10-min. flight centred 10, 20, 30 and 40 min. from the centre of the transition zone

(ii) The difference of the average temperature from the average for the interval in the centre of the transition zone was calculated

(iii) The mean temperature profile was plotted from the mean value of the difference obtained in stage (ii)

(iv) Average values of the depression of the frost point were calculated for the intervals at distances 10, 20, 30 and 40 min. from the centre of the transition zone

(v) The mean frost-point profile was plotted by subtracting these average frost-point depressions from the corresponding temperatures of the mean temperature profile

FIG. 5—AVERAGE PROFILES OF TEMPERATURE AND FROST POINT ACROSS FRONTS AS DERIVED FROM AIRCRAFT OBSERVATIONS

be applied. The average value of the slope (tan θ) obtained by the three methods for these cases is as follows :—

(i) from radio-sonde data alone	0·013
(ii) from vertical and horizontal thickness of the frontal zone ..	0·019
(iii) from the positions of aircraft intersections with the frontal zone	0·018

From the figures in the Appendix it will be seen that although the three estimates agree as to the order of magnitude of the slopes of the fronts and there is some correlation between them, numerical agreement is poor. Although the extreme estimates are probably in error there is reasonably good evidence that the slopes varied from 1 in 250 to 1 in 30.

Results such as those of the preceding paragraphs can be explained if a sloping frontal zone exists, but the position of its boundaries in both horizontal and vertical soundings is subject to considerable uncertainty (say 40 miles in the horizontal and 2,000 ft. in the vertical). Such uncertainty exists partly because the observations are not synchronous and cannot be placed with sufficient accuracy, but also, perhaps more important, because the irregularity of the temperature profile in the vertical and horizontal precludes the exact identification of a frontal zone.

§ 5—IRREGULARITIES OF THE TEMPERATURE PROFILE

As has been seen, important difficulties in interpreting the observed temperature profiles arise from the presence of irregularities of temperature which are not representative of the general temperature field associated with the front. Such irregularities are sufficient to reverse the general horizontal temperature gradient and make it impossible to decide with any certainty where the limits of the frontal zone lie. An example of particularly large irregularities of temperature is provided by the observations at 850 mb. on June 12, 1951 (see Fig. 6). This flight was made through an active cold front, and although there is an overall rise of temperature from west to east it is clearly quite impossible to define a frontal zone. On the other hand, on such temperature profiles as those for November 3, 1950 (see Fig. 1) the irregularities appear only as embroidery upon a clear general trend.

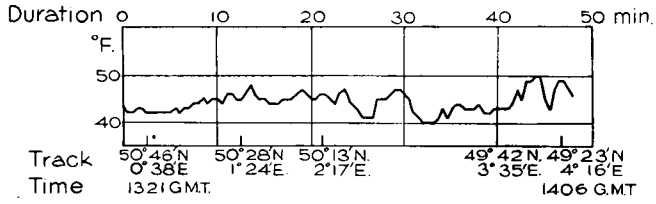


FIG. 6—PROFILE OF TEMPERATURE AT 850 MB., 1320–1405 G.M.T., JUNE 12, 1951

Track : 50°46'N. 0°38'E. to 49°23'N. 4°16'E.

A measure of the magnitude of these irregular temperature fluctuations is given by the standard departure of individual temperature observations from a 5-min. running mean (roughly over 18 miles). The value of this standard departure for flight in clear air, 0·50° F., is appreciably less than that for cloud, 0·70° F. These values are taken from observations for which the mean could be based on observations entirely within either clear air or cloud, and thus refer to points more than 2 min. flying time from the edge of cloud or precipitation. It is significant that the standard departure, 0·84° F., for the remaining observations which were all near the boundary of cloud or precipitation is greater than that for either clear air or cloud. On most of the flights temperatures were available only to the nearest degree, and values of the standard departure less than 0·5° F. are unreliable, but it is very unlikely that the differences

between clear, cloudy and transitional air arise from an accident of the rounding-off procedure. It is possible that the differences are due to a greater random error of temperature measurement in cloud than in clear air, although it seems more likely that the differences are real.

The average magnitude of the temperature irregularities decreases with height above ground, the standard departure from the running mean falling from about 0·8° F. at about 5,000 ft. to less than 0·4° F. at about 15,000 ft. This marked trend is due partly to the greater proportion of observations in cloud and transitional air at the lower levels and partly to the decrease of the irregularities with height in cloudy and transitional air. There is only a slight tendency for the irregularities of temperature in clear air to decrease with height. These facts can be seen clearly in Fig. 7 in which the standard departure of temperature from the running mean is plotted against the height of the aircraft for observations on individual horizontal legs. Separate diagrams indicate the variation with height of temperature departures in cloudy, clear and transitional air.

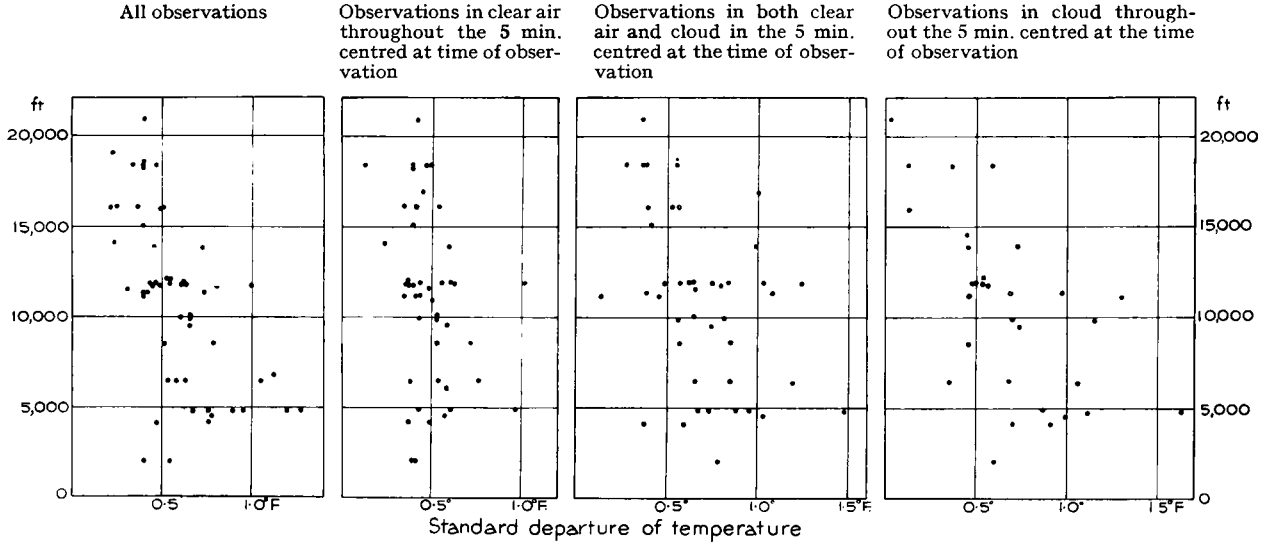

All observations
Observations in clear air throughout the 5 min. centred at time of observation
Observations in both clear air and cloud in the 5 min. centred at the time of observation
Observations in cloud throughout the 5 min. centred at the time of observation
ft
20,000
15,000
10,000
5,000
0
0·5
1·0°F
1·5°F
Standard departure of temperature

FIG. 7—STANDARD DEPARTURE OF TEMPERATURE FROM 5-MIN. RUNNING MEAN, PLOTTED FOR INDIVIDUAL HORIZONTAL LEGS AS A FUNCTION OF HEIGHT

There was very little difference between the average magnitude of the temperature irregularities in the warm and cold air masses or between these and the frontal zone; the mean values of the standard departure were warm air 0·59° F., frontal zone 0·70° F., cold air 0·69° F., and the differences are not great enough to be regarded as significant.

Although significant irregularities of temperature occur away from cloud and precipitation, there can be little doubt that the largest fluctuations of temperature arise on the borders of cloud and rain from the processes of condensation, evaporation and precipitation. Changes of temperature of 5° F. or more in 2–3 min. (in a horizontal distance of 6–10 miles) were observed on several occasions. Temperatures did not consistently rise or fall as the aircraft entered cloud, although on the average the temperature within the cloud appeared to be about 0·9° F. lower than in the adjacent air outside the cloud—a difference which can probably be explained by the fact that the correction applied to the thermometer readings for the compression of the air as it passes over the thermometers takes no account of the cooling effect of the evaporation of cloud droplets. Irregularities of temperature such as those discussed here are not peculiar to frontal regions. Numerous observations of similar irregularities have been made by the Meteorological Research Flight within individual air masses[2], and their magnitude probably differs between fronts and air masses only on account of the greater frequency of cloud and precipitation in association with fronts.

§ 6—HUMIDITY IN FRONTAL REGIONS

Observations of dew point above 32° F. and frost point below 32° F. were made throughout most of the flights. The frost point (and dew point) were found to be much more variable than the temperature; fluctuations of the order of 8° or 9° F. over distances of 15 miles occurred throughout much of the flights. These are some five times as great as the corresponding variations of temperature. Similar irregularities of frost point have been studied by Frith[3] within individual air masses and are not specifically associated with frontal regions.

The aircraft observations of humidity are not sufficient to establish the complete horizontal and vertical distribution of humidity which accompanied the fronts. However, it was found possible to use the dew points reported by the routine radio-soundings to prepare a vertical dew-point cross-section through each front. Although such sections cannot show the complex and irregular distribution of water vapour which the aircraft observations demonstrate, nevertheless comparison between the cross-sections and the aircraft observations of humidity shows that the cross-sections are sufficiently accurate to indicate the broad features of the humidity pattern.

A feature, more or less well developed on all the dew-point cross-sections, was a tongue of relatively dry air extending downward in the vicinity of the front and tilted in the same direction as the front (see Figs. 2 and 3). The dry tongue was less well developed in association with the cold fronts than with the warm fronts; it extended down to an average pressure level of 700 mb. in cold fronts and 800 mb. in warm fronts. In about half the fronts the driest air was found within the frontal transition zone itself, but there were also occasions when it was found on either the cold or the warm sides of the transition zone. Some striking changes of frost point occurred as the aircraft entered or left the dry tongue; a good example, that of January 4, 1952, is reproduced in Fig. 8. About half the flights showed a sharp transition from moist to dry air and the change of frost point averaged about 37° F. in 35 miles on these flights. Some of the sharpest transitions gave changes of more than 40° F. in 20 miles.

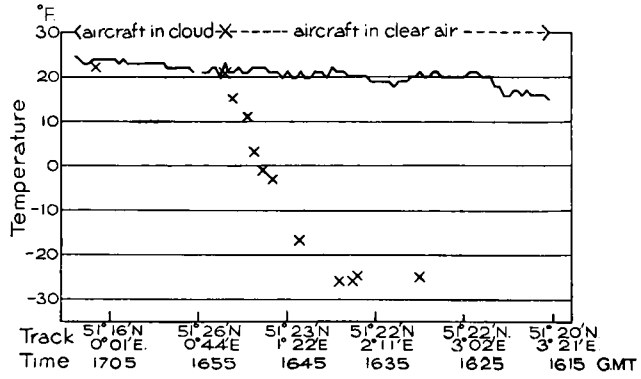


FIG. 8—PROFILE OF TEMPERATURE AND FROST POINT AT 800 MB., 1615–1710 G.M.T., JANUARY 4, 1952
Track: 51°20'N. 3°21'E. to Farnborough
Temperature is indicated by a continuous curve, frost point by crosses

Average profiles of frost point across the frontal zones have been computed from the aircraft observations for cold fronts and warm fronts; these are reproduced in Fig. 5. The results depend slightly on the particular technique of averaging, and the method adopted here is explained below the diagram. However, the essential features are not in doubt. At warm fronts the profile shows a steady change from moist warm air to dry cold air over a distance of about 300 miles whereas for cold fronts the average profile indicates a dry transition region between two relatively moist air masses—the dry zone is about 100 miles wide. The cold-front profile confirms the

existence of the dry tongue described in the preceding paragraph ; the reason for its appearance only on the extreme right of the average profile for warm fronts is to be found in the variation in the position of the dry tongue relative to the front, together with the dryness of the cold air mass.

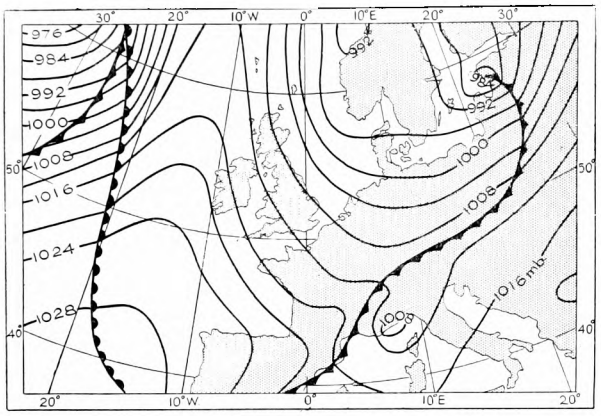
The very rapid increase of frost point as the cloud is approached may be noted in Fig. 8 ; this is not uncommon. Table I gives the average difference between the temperature at the edge of the cloud and the frost point at points within the clear air distant from the cloud by ½, 1, 1½.....min. flying time. It shows that the humidity falls off rapidly away from the cloud so that at a distance of less than 10 miles the average depression of the frost point is 10° F. ; it changes only slowly with farther distance from the cloud. From these results it seems improbable that, in the analysis of free-air humidity observations, extrapolation of the humidity and temperature observations to saturation can accurately predict the position of cloud masses.

TABLE I—AVERAGE DIFFERENCE BETWEEN FROST POINT AT VARIOUS DISTANCES FROM THE EDGE OF A CLOUD AND THE TEMPERATURE AT THE CLOUD BOUNDARY

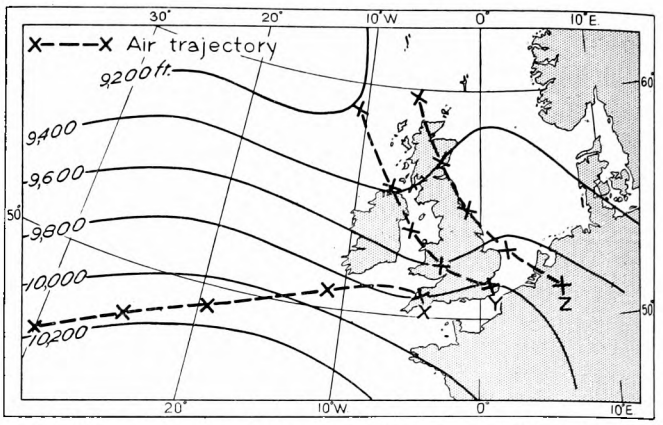
					minutes					
Flying time from cloud edge ..	½	1	1½	2	2½	3	3½	4	4½	5
					miles					
Approximate distance from cloud edge	2	4	5	7	9	11	13	15	16	18
					degrees Fahrenheit					
Temperature at cloud edge minus frost point in the clear air	5·9	7·8	8·3	9·0	10·6	13·0	13·0	12·0	11·6	13·3
Temperature at cloud edge minus temperature in the clear air	−0·3	−0·6	−0·6	−0·7	−0·8	−0·8	−0·8	−0·7	−0·7	−0·8

An interesting question concerns the source of the dry air which occurs in the " dry tongues ". In order to study this, trajectories of the air within the dry tongue and of the adjacent moister air were drawn on the basis of routine contour charts for appropriate pressure levels. Although the trajectories are necessarily rather uncertain, the analysis shows that it is reasonable to attribute the humidity differences primarily to large-scale horizontal air movements. The dry air accompanying a warm front seems to have been derived from the subsided air of the preceding ridge and may not have undergone any recent large vertical movement when found in or just ahead of the frontal zone. A typical example is that of January 4, 1952 for which three representative 700-mb. trajectories are shown in Fig. 9 terminating at the points indicated in the cross-section ; aircraft observations of temperature and frost point are given in Fig. 8. It is clear that air with widely different histories entered into the frontal region. The air within the dry tongue was off the west coast of Scotland 24 hr. earlier, close to the surface ridge of high pressure. The Stornoway radio-sonde showed that the air in that region was already notably dry, the dew point being reported as −22° F. at 700 mb. and −41° F. at 650 mb. The temperature is somewhat uncertain because the trajectory passed some 150 miles west of Stornoway. It is doubtful if the Stornoway 700-mb. temperature at 1500 G.M.T. can be regarded as applicable at this point, because between 1500 and 2100 G.M.T. the temperature increased from 3° to 9° F. This was probably largely due to subsidence, but if it was due to advection then temperature must have increased rapidly to the west of Stornoway. In either case it is clear that the subsidence which effectively dried the air took place in the ridge of high pressure and some 18 hr. or more before it was sampled by the aircraft.

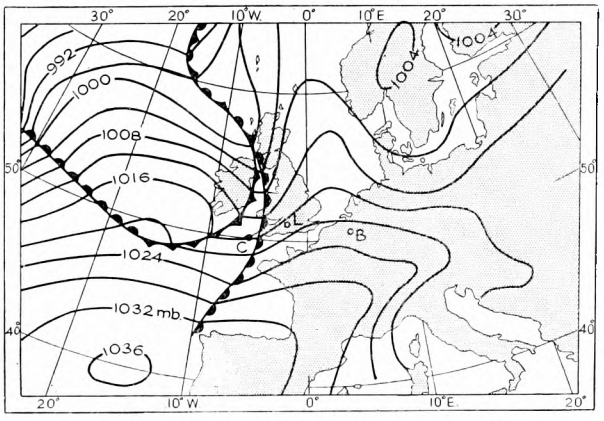
A particularly interesting case is that of the cold front of November 3, 1950, in which very dry air was found in the transition zone. Relevant trajectories for air moving at the 500-mb. level are shown in Fig. 10. There was undoubtedly a very marked confluence of air from widely



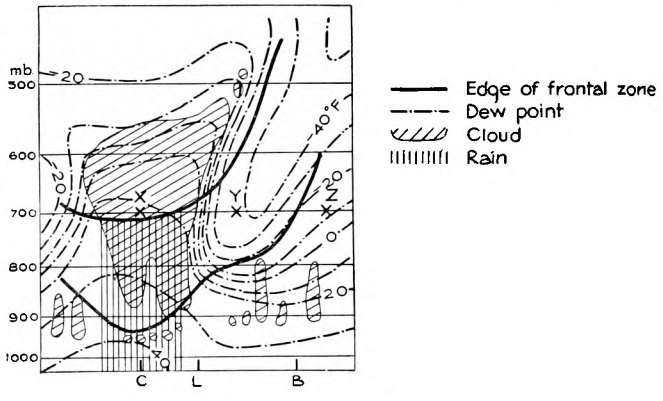
Surface chart, 1500 G.M.T., January 3, 1952



700–mb. contour chart, 1500 G.M.T., January 4, 1952 and 24-hr. trajectories at 700 mb. terminating at that time



Surface chart, 1500 G.M.T., January 4, 1952

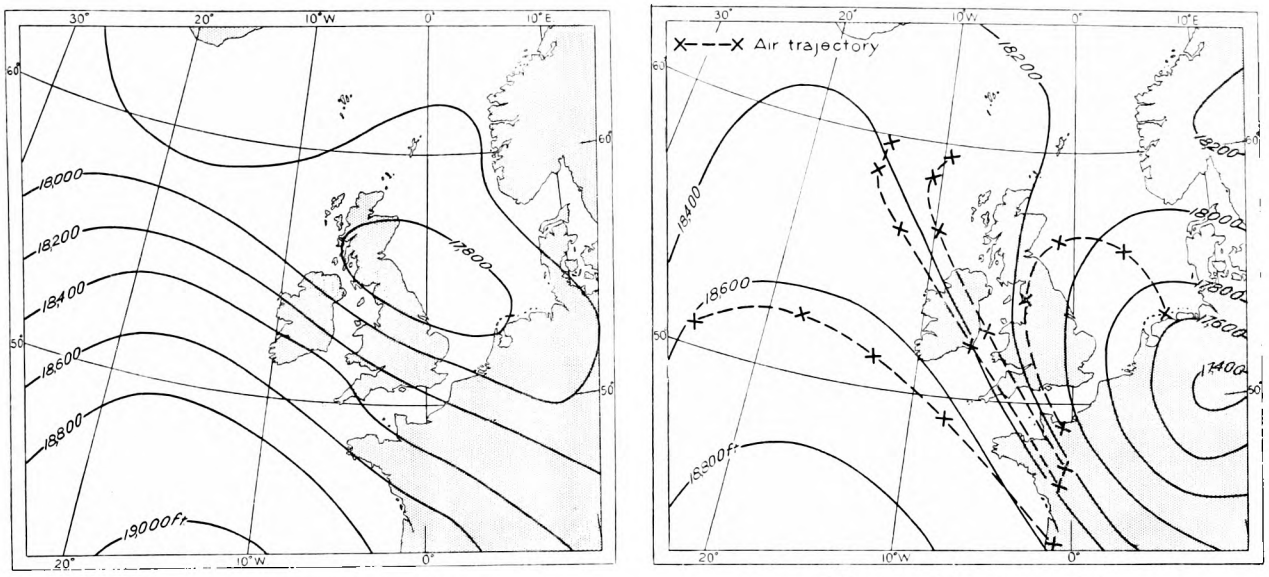


Cross-section, 1500 G.M.T., January 4, 1952

FIG. 9—SYNOPTIC SITUATION AND CROSS-SECTION, JANUARY 3–4, 1952
C = Camborne, L = Larkhill, B = Brussels

separated areas, and the air which was in or close to the frontal zone at the time of the flight was not associated with any frontal zone 24 hr. earlier. The exact source of the air which lay in the transition zone at 1500 G.M.T., November 3, 1950 is uncertain, but it appears most likely that it was off the coast of north-west Scotland. The air in this region was cold and the tropopause low (373 mb. at Stornoway at 1500 G.M.T., November 2), and if air moved adiabatically to the frontal zone over France, where the temperature was between −8° F. and 0° F. at 500 mb., then it would have had to descend by about 140 mb. so that stratospheric air was brought down to the 500-mb. level. Such vertical motion casts doubt on the value of a trajectory based on the 500-mb. level, but if a trajectory is interpolated between 500 and 300 mb. making allowance for the vertical motion little material difference is introduced. Trajectories of air on the warm and cold sides of the frontal zone indicate little change of temperature at 500 mb., and the greatest descent of the air appears to have been confined to a limited band of air from north-west of Scotland, which was drawn out into a narrow filament as it passed into the entrance region of the jet stream. Thus the very dry transitional air observed on November 3, 1950 may have been derived from the stratosphere within the preceding 24 hr.

On only two other occasions was the upper part of a cold front investigated (on April 27, 1951 and August 1, 1951). Both showed very dry air in or near the frontal zone. However, trajectories drawn to show the history of the air at the 500-mb. level indicate that warm, cold and transitional



1500 G.M.T., November 2, 1950

1500 G.M.T., November 3, 1950

FIG. 10—500-MB. CONTOUR CHARTS, NOVEMBER 2–3, 1950

The 24-hr. trajectories at 500 mb. between the two charts are shown on the chart for November 3, crosses indicating the positions at 6-hr. intervals

air had moved horizontally on roughly parallel trajectories through the jet-stream system during the previous 24 hr. Whether any process similar to that of November 3, 1950 had taken place at an earlier stage cannot be established owing to lack of observations in the relevant areas.

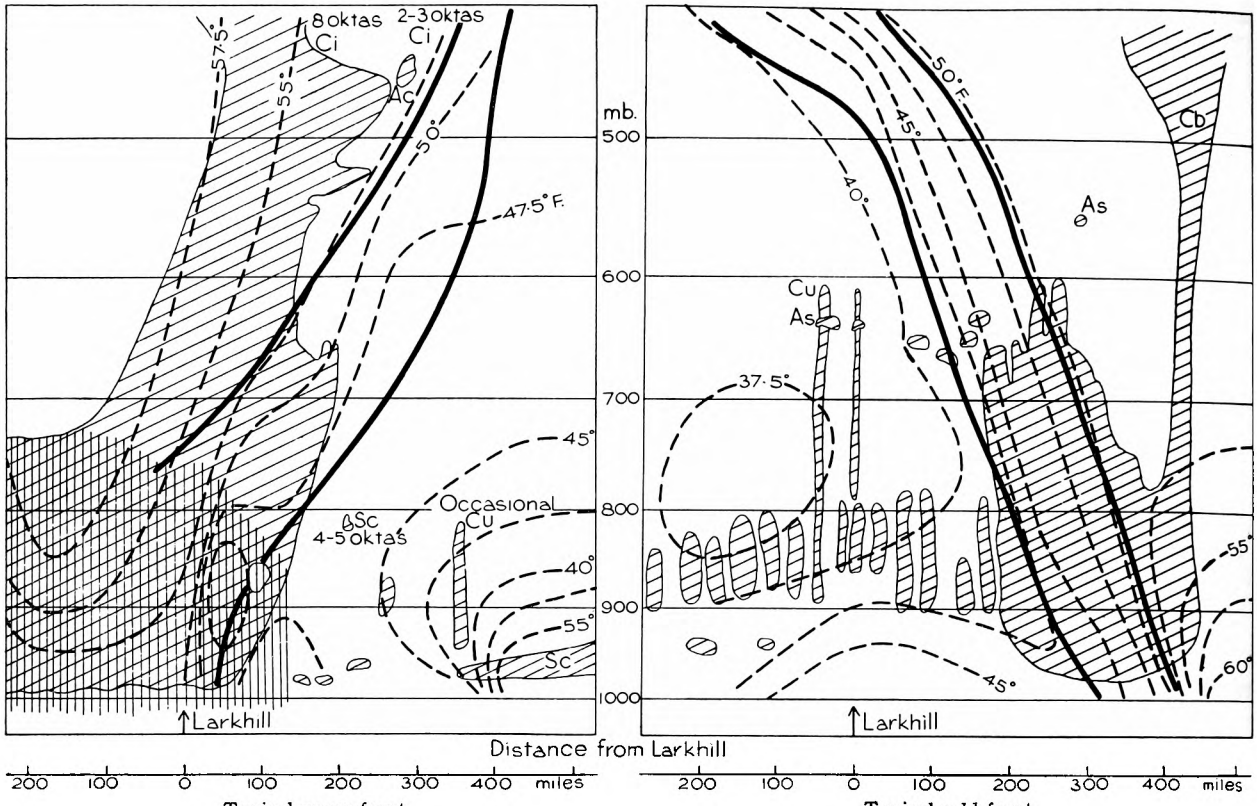
§ 7—CLOUD OBSERVATIONS IN ASSOCIATION WITH FRONTS

From the observations of cloud made by Meteorological Research Flight aircraft at two different levels together with the observations of surface reporting stations, it was possible to form a reasonably coherent picture of the distribution of cloud accompanying the fronts through which the flights were made. Figs. 3 and 11 illustrate the type of cross-section which it was possible to construct.

The distribution of cloud varied widely between individual fronts, but the fronts which were investigated may be grouped as in Table II to demonstrate the main features of the cloud structure.

TABLE II—ANALYSIS OF CLOUD STRUCTURE AT FRONTS FROM THE OBSERVATIONS OF METEOROLOGICAL RESEARCH FLIGHT AIRCRAFT

	No. of cases
Main cloud mass in the warm air mass with only a relatively small extension into the transition zone	9
Main cloud mass partly in the warm air mass and partly in the transition zone	7
Frontal cloud only in or near boundaries of transition zone (these were all weak fronts and cloud was patchy and not extensive)	4
Frontal cloud consisted of a mass of convective cloud in cold air and transition zone—front thermally ill defined	1
Solid mass of cloud in cold air mass (the cloud was probably associated with an old occlusion ahead of the main thermal front—see further notes in §9, p. 19)	1



Typical warm front
1500 G.M.T., March 6, 1952

Typical cold front
1500 G.M.T., April 27, 1951

FIG. 11—CROSS-SECTIONS OF CLOUD AND WET-BULB POTENTIAL TEMPERATURE REQUIRED FOR SATURATION AT THE OBSERVED TEMPERATURE

The broken lines indicate the wet-bulb potential temperature required for saturation

The amount and extent of cloud encountered varied considerably. Several fronts were crossed without the aircraft flying through any cloud at the selected level; at the other extreme, a horizontal flight of almost 300 miles was made entirely in cloud (the case is further discussed in § 9, p. 19). An indication of the variation of the amount of cloud with height is given by Table III which shows the proportion of total duration of the horizontal flights which took place in cloud. As each front was only investigated at two levels and those not often widely separated, the figures in Table III are no doubt strongly influenced by the accidental choice of fronts and flight levels. However, the fairly uniform distribution of cloud at all levels up to 15,000 ft. and the relatively smaller amounts above 15,000 ft. conform with expectation and are probably real.

When viewed from below the frontal cloud masses were generally reported as being of layer type; altostratus, nimbostratus or altocumulus. Reports of the cloud from above were not so numerous but were again mainly of layer type. Reports of layer cloud predominate in the cold fronts as well as in the warm fronts, but convective cloud was found associated with the frontal cloud mass in all of the 5 cold fronts for which information is available. Convective cloud was reported in association with the frontal cloud of 6 out of the 17 warm and quasi-stationary fronts; most of these reports are consistent with the unstable or near neutral lapse rates in the regions concerned.

The two cross-sections of cloud structure in Fig. 11 have been reproduced to illustrate some of the more common features of the cloud distribution. It would be wrong to regard these sections as typical of the flights as a whole, but some of their features occurred several

TABLE III—DURATION OF FLIGHT IN CLOUD AND CLEAR AIR AT VARIOUS LEVELS DURING SERIES OF FLIGHTS

Height range	Duration of flight in cloud	Duration of flight in clear air	Proportion of flight in cloud
ft.	min.	min.	per cent.
Above 15,000	139	627	20
10,000–15,000	386	868	31
5,000–10,000	193	367	34
Below 5,000	197	415	32
All levels	915	2277	29

times in the small sample which was available, and these diagrams may perhaps be regarded as illustrating common types of cloud structure at the more active warm and cold fronts.

The cross-section for March 6, 1952 in Fig. 11 shows a solid mass of cloud some 200 miles broad at most levels and extending upward well above the higher flight level of 650 mb. The upper limit of the cloud is uncertain, but has been inserted on the basis of the humidities reported on the radio-sonde soundings. A noteworthy feature, which also occurs at other warm fronts, is that the general inclination of the cloud mass is steeper than that of the front. The broken lines of Fig. 11 indicate the wet-bulb potential temperature required for saturation at the observed temperature. Since the wet-bulb potential temperature in the upper part of the cloud lies mainly between 52° and 58° F., the air comprising this part of the cloud may have been derived from the lower layers of the warm air mass. The lower part of the cloud lying within the frontal transition zone has a lower wet-bulb potential temperature. If it has been derived from the warm air mass it must have been subject to considerable cooling by precipitation. It is more probable that this cloud has been formed in cold or transitional air which has been moistened by precipitation.

Noteworthy features of the cloud structure at the cold front of April 27, 1951 (see Fig. 11) are the narrow area of large convection cloud in the warm air mass close to the surface front, and the absence of cloud in the frontal zone in the upper troposphere. Only 5 other cold fronts were investigated (and for one the cloud observations are incomplete). However, the frontal zone was free of cloud in the upper troposphere in all 6 fronts, and a rather narrow band of cloud with considerable vertical development occurred in the warm air above the surface front in 4 out of the 5 fronts for which this region was explored. The solid mass of cloud which appears on April 27 in the transition zone below 650 mb. was found only in this case, but this front was the most active of the series and such structure may be more common than its occurrence once in 5 fronts might suggest. On this occasion the aircraft passed through the top of the cloud mass which lay in the frontal zone and reported marked cumuliform structure. This is surprising in view of the likelihood of a stable vertical lapse rate in the frontal zone (confirmed by the Trappes radio-sonde). Possibly, however, the vertical convection currents did not extend through any considerable depth.

§ 8—TURBULENCE IN ASSOCIATION WITH FRONTS

The average level of turbulence recorded in the course of the frontal flights was slightly greater in cloud than in clear air and significantly greater still near the boundaries of cloud and precipitation. Frequencies of various levels of turbulence over 5-min. intervals entirely in cloud, entirely in clear air and partly in cloud or precipitation are given in Fig. 12. The difference of the average level of turbulence is very slight between the warm, cold and transitional air masses

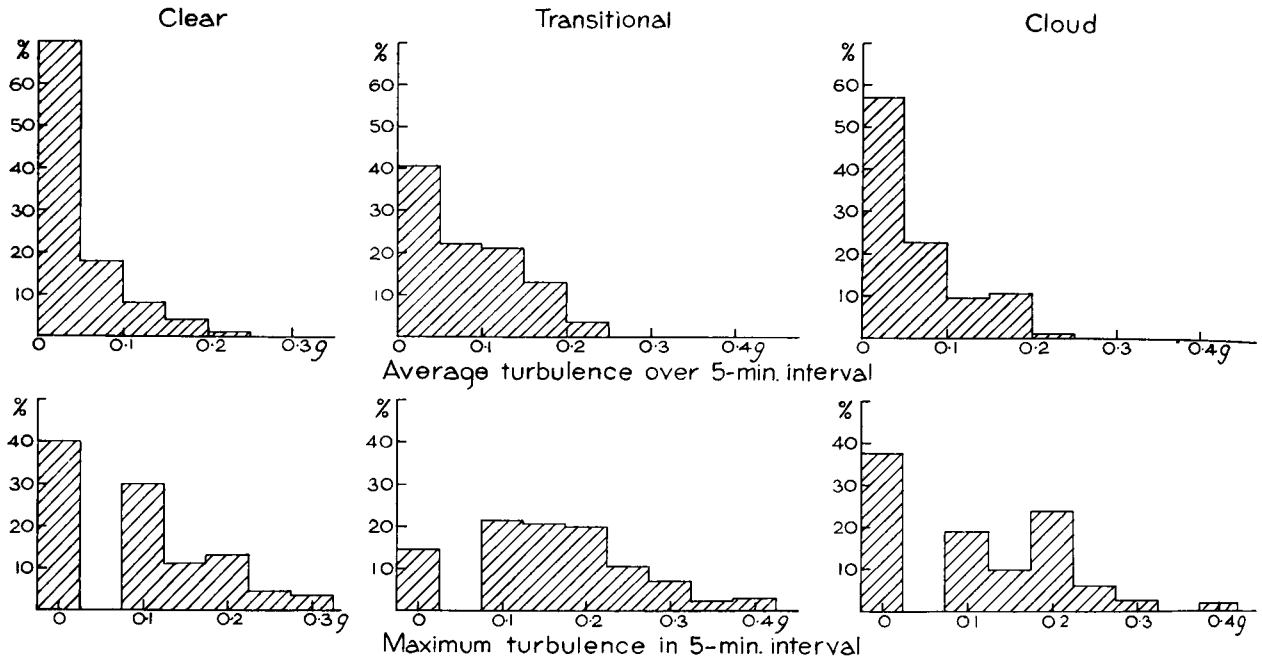


FIG. 12—PERCENTAGE FREQUENCY OF VARIOUS LEVELS OF TURBULENCE IN CLEAR AIR, IN CLOUD AND IN THE TRANSITIONAL REGION NEAR BOUNDARIES OF CLOUD OR PRECIPITATION

although it is probably significant that the lowest average is found in the cold air where less cloud is encountered. The turbulence tends to be somewhat greater in the first 5,000 ft. above the ground but no variation with height above 5,000 ft. was noted.

Probably of greater interest is the occurrence of bumps of $0 \cdot 3g$ or greater. Bannon[4] quotes $0 \cdot 4g$ as the lower limit of heavy turbulence; thus, by considering bumps of $0 \cdot 3g$ and more, some " moderate " turbulence will be included along with the severe cases. Even so, gusts of $0 \cdot 3g$ were encountered in less than 5 per cent. of the 5-min. intervals into which the flights were divided for this analysis. On the other hand one or more gusts of this magnitude were encountered somewhere on most of the flights.

Gusts of $0 \cdot 3g$ or more were encountered on 20 of the horizontal legs. Only two of these occasions occurred in clear air without cloud or rain in the vicinity. The cause of turbulence on these two occasions is obscure, because the wind shear does not appear to have been unusually great, nor could the Richardson number have been much lower than normal—certainly not as low as 1. On one of these occasions (November 3, 1950, 485 mb.) the bumpiness was found above the upper boundary of a well defined cold front (see Fig. 2); the other observation of clear-air bumpiness of $0 \cdot 3g$ occurred on May 23, 1951 at 500 mb. close to the lower boundary of a warm front. On the first occasion the bumpiness was very limited in extent; the extent on the second occasion is unknown because the aircraft descended out of the area.

Of the remaining 18 occasions of gusts of $0 \cdot 3g$ or more, 13 were associated with reports of cumulus cloud, thunderstorms or lapse rates in excess of the saturated adiabatic, and there seems little doubt that these arose from ordinary convective vertical motion. Two cases of $0 \cdot 3g$ bumps occurred in cloud with a lapse rate quite stable for moist air; however, they were both associated with a strong vertical wind shear and a Richardson number probably less than 1. Three occasions were accompanied by lapse rates close to the saturated adiabatic. Two of these had wind shears of 6 kt./Km. and 24 kt./Km. respectively and the Richardson number must have been less than 1; the wind shear in the third case is uncertain but was up to 5 kt./Km. over neighbouring areas. The situations in which gusts of $0 \cdot 3g$ or more were found are summarized in Table IV.

TABLE IV—ANALYSIS OF SITUATIONS IN WHICH TURBULENCE OF $0{\cdot}3g$ OR MORE WAS OBSERVED

Situation	No. of cases
Associated with convective phenomena, cumulus, thunder, etc.	13*
In cloud with lapse rate near saturated adiabatic and strong wind shear ..	3
In cloud with stable lapse rate and strong wind shear	2
In clear air not close to cloud or precipitation (no obvious explanation) ..	2
Associated with lenticular cloud	1*

* On one horizontal flight two distinct occurrences of turbulence occurred; one occurred in irregular frontal cloud with lapse rate near saturated adiabatic and is included under convective phenomena, and the other occurred just below lenticular cloud.

§ 9—NOTES ON SOME INDIVIDUAL FRONTS

June 26, 1951.—On June 26, 1951 (see Fig. 13) a flight was made primarily to investigate the warm front to the south-west of the British Isles. Rain was falling over central England but this was more closely associated with an old depression over the North Sea than with the approaching front. It is not easy to place the frontal zone in the free atmosphere but the only

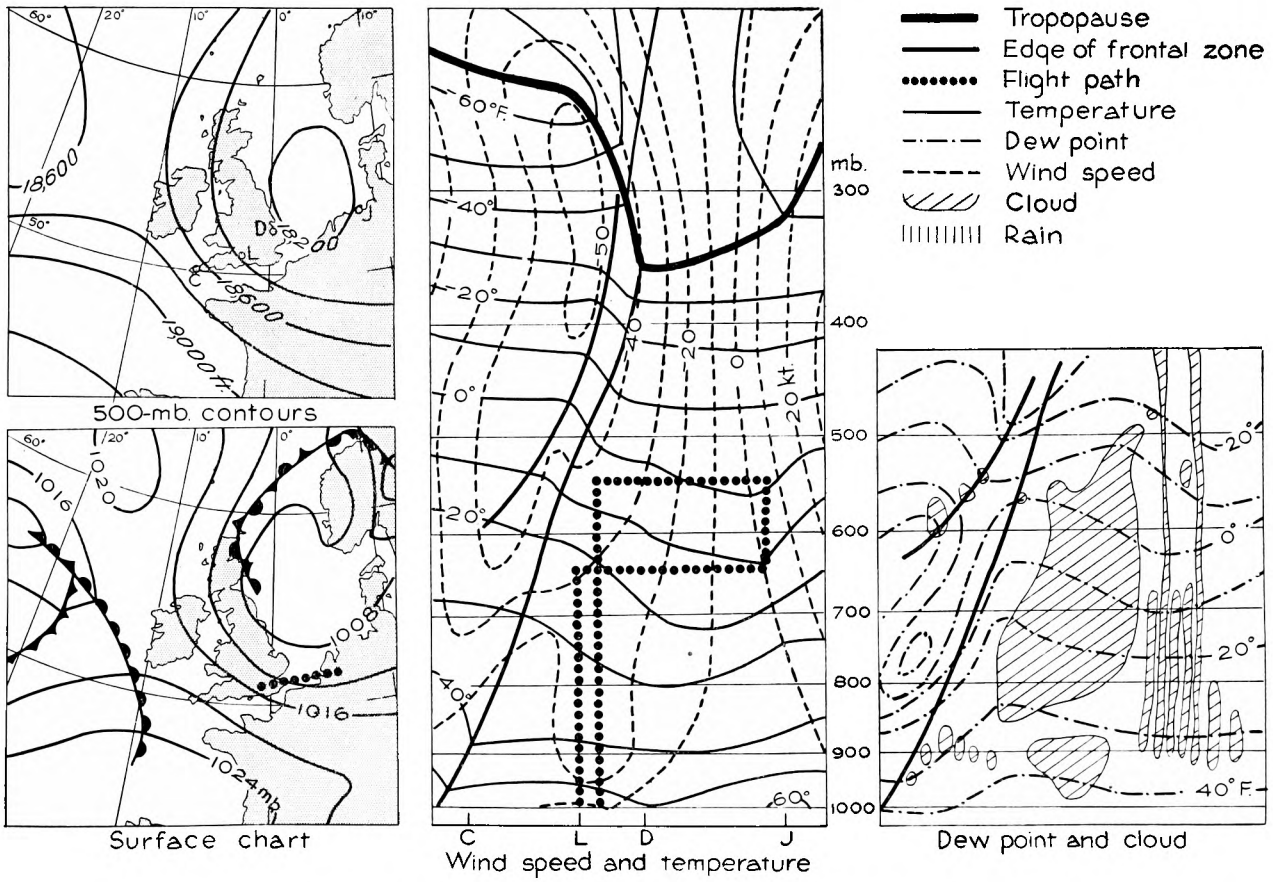


FIG. 13—SYNOPTIC SITUATION AND CROSS-SECTIONS, 1500 G.M.T., JUNE 26, 1951
C = Camborne, L = Larkhill, D = Downham Market, J = Jever

sloping baroclinic zone which can be identified appears to have been situated to the west of and above the area investigated by the aircraft. The rain over England was falling from an extensive mass of cloud lying in a baroclinic region within the cold air ; at the flight levels (550 and 650 mb.) the cloud was rather tenuous and flying conditions notably smooth. The moisture necessary to form this mass of cloud and precipitation was certainly derived from the old depression over the North Sea, and the old occlusion could have entered into the area. However, there is no indication on the vertical cross-sections of any occluded warm air mass, and it seems more appropriate to regard the cloud and precipitation as due to " development " taking place in the general baroclinic zone and producing the most significant " weather " where the air was moist and easily saturated by lifting.

August 17, 1951.—On August 17, 1951 the structure of an old occlusion was investigated and the relevant synoptic charts and cross-sections are reproduced in Fig. 14. Noteworthy features are :—

(i) Shallow nature of the frontal structure.

(ii) Warm dry air above the inversion behind the front.

(iii) Relatively shallow layer of moist air which produced the cloud masses. On account of its wet-bulb potential temperature it appears to have been derived from the lowest 4,000 ft. of the air behind the front.

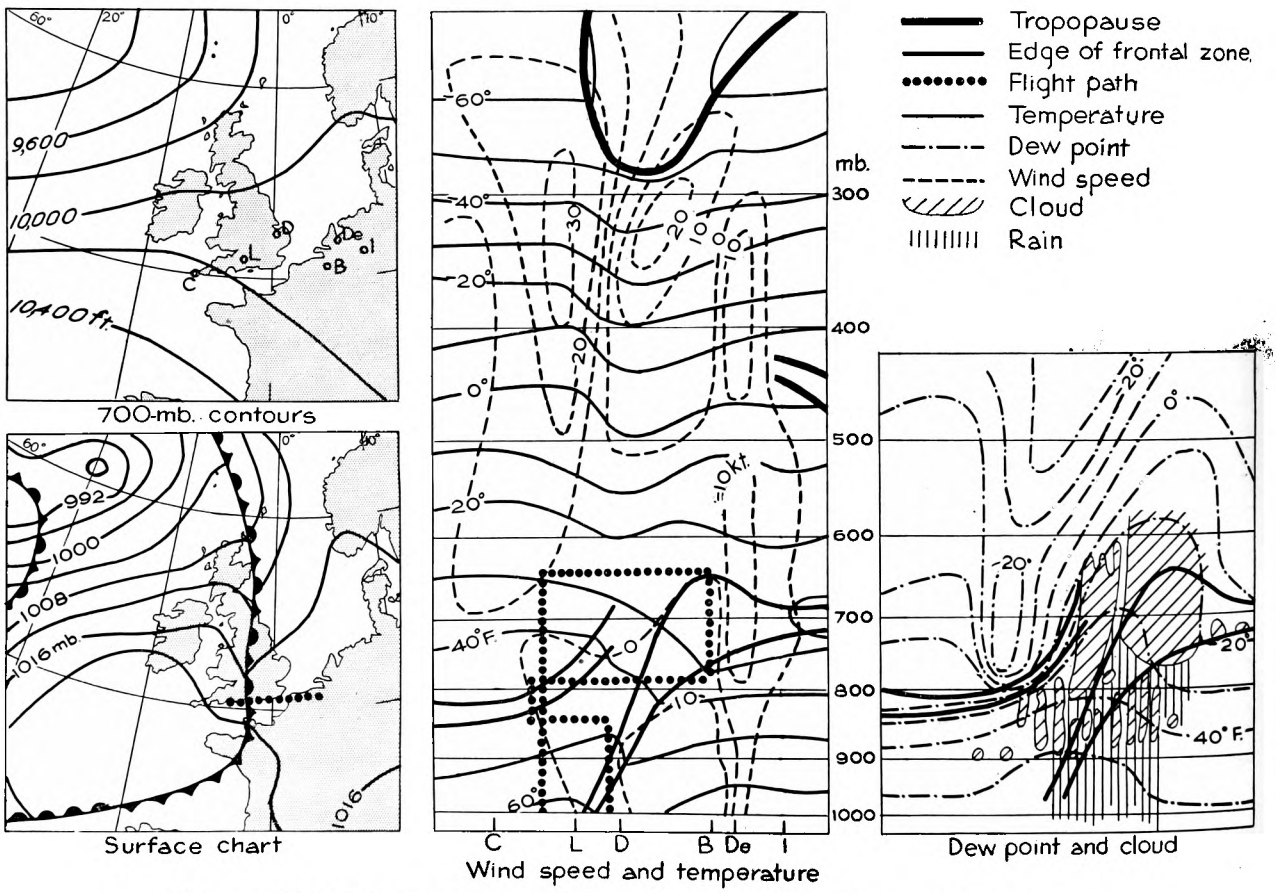


FIG. 14—SYNOPTIC SITUATION AND CROSS-SECTIONS, 1500 G.M.T., AUGUST 17, 1952

C = Camborne, L = Larkhill, D = Downham Market, B = Brussels, De = De Bilt, I = Iserlohn

(iv) Unstable character of the cloud mass and the associated irregular horizontal profile of temperature (see Fig. 1).

(v) Persistent bumpiness on all sections of the flight except in the warm dry air above the inversion to the west of the front. Bumps reached 0·3*g* occasionally at all flight levels.

August 23, 1951.—The flight of August 23, 1951 is interesting as showing that the structure of a warm front may be weak and ill defined up to within 300 miles of the centre of a depression. Fig. 15 shows the synoptic situation and cross-section through the front. The frontal surface is

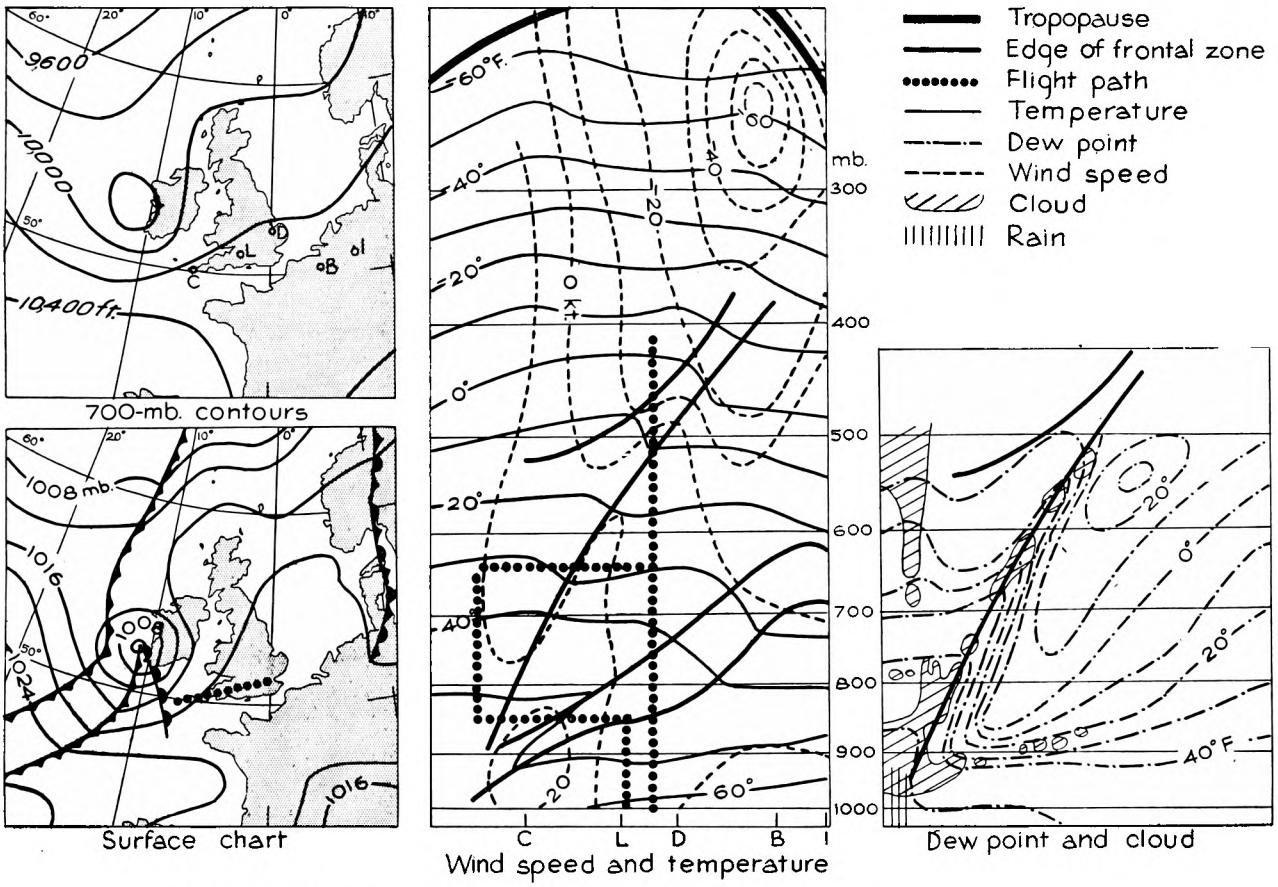


FIG. 15—SYNOPTIC SITUATION AND CROSS-SECTIONS, 1500 G.M.T., AUGUST 23, 1951
C = Camborne, L = Larkhill, D = Downham Market, B = Brussels, I = Iserlohn

difficult to place on the cross-section, and the cloud appears to lie mainly in two broken layers at the base of the two sloping stable layers of the atmosphere. The existence of somewhat thicker cloud layers above the surface front is also noteworthy.

November 5, 1951.—The flight of November 5, 1951 (see Fig. 16) demonstrated the existence of a very broad and steeply sloping baroclinic zone in association with a slow-moving front. The cloud must have been formed by vertical motion in the baroclinic zone ; no material part of the moisture can have been supplied by precipitation from the overlying warm air because the slope of the front was so steep (1 in 30) that a large part of the transition zone was not vertically beneath any part of the warm air. The broad belt of cloud and precipitation is interesting.

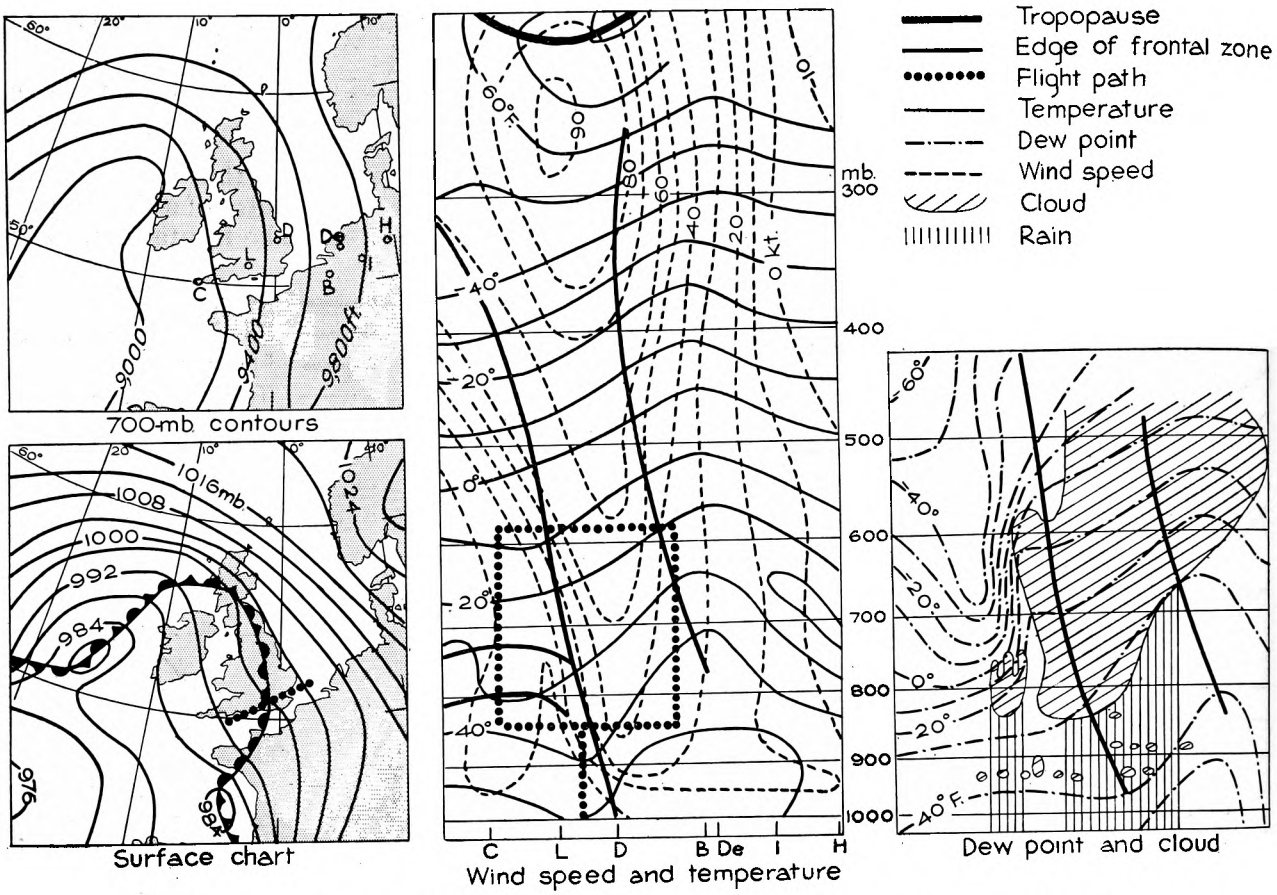


FIG. 16—SYNOPTIC SITUATION AND CROSS-SECTIONS, 1500 G.M.T., NOVEMBER 5, 1951
C = Camborne, L = Larkhill, D = Downham Market, B = Brussels,
De = De Bilt, I = Iserlohn, H = Hanover

§ 10—CONCLUSIONS

(1) The present series of flights indicates the great complexity of the atmosphere in frontal regions ; no idealized frontal model can adequately represent an individual front.

(2) The flights confirm that fronts are associated with a sloping baroclinic zone, and that about half the total air-mass contrast of temperature is concentrated in a region with a width usually of 100–200 miles.

(3) Small-scale irregularities of temperature of the order of 1° F. are sufficient to prevent any clear delimitation of a frontal zone by distinct boundaries except in association with the upper part of some cold fronts where the air is usually free from cloud.

(4) The largest irregularities of temperature are associated with the physical processes of condensation, precipitation and evaporation, and they occur near the boundaries of cloud and precipitation. The most striking gradients of temperature arise from these causes and reach 5° F. in less than 10 miles.

(5) Some very dry air is usually found in frontal regions in close juxtaposition to cloud and precipitation. Its presence can be adequately explained by large-scale movements of the air which are primarily horizontal ; the air has been dried by subsidence but this may have been 24 hr. or

more before it was observed in the frontal region. The presence of dry air is no indication of descending motion in the front, nor of the absence of adequate moisture for frontal rain. Thus reported humidity on individual radio-sonde soundings cannot provide a forecaster with any reliable indication of the activity of a front.

(6) Cloud structure of fronts is very variable. The main frontal cloud masses are usually formed within the warm air mass, and extend into the transition zone by the evaporation and re-condensation of rain or snow. However, observations on June 26, 1951 and November 5, 1951 suggest that frontal cloud can also form in the cold air or transition zone, if adequate moisture is available there.

(7) Fronts are not ordinarily regions of particularly marked turbulence. Most of the moderate or severe turbulence is associated with the ordinary processes of convection, cumulus cloud, thunderstorms, etc. Some cases were also observed in association with strong vertical wind shear and two occurrences of $0 \cdot 3g$ bumps in clear air remain unexplained.

BIBLIOGRAPHY

1. SAWYER, J. S. ; Effect of atmospheric inhomogeneity on the interpretation of vertical temperature soundings. *Met. Mag., London*, **82**, 1953, p. 257.

2. FRITH, R. ; Atmospheric inhomogeneity on the 50-Km. scale. *Met. Res. Pap., London*, No. 583, 1950.

3. FRITH, R. ; Small-scale temperature and humidity patterns in the free air. *Met. Res. Pap., London*, No. 402, 1948.

4. BANNON, J. K. ; Meteorological aspects of turbulence affecting aircraft at high altitude. *Prof. Notes met. Off., London*, **7**, No. 104, 1951.

APPENDIX—LIST OF FRONTS EXPLORED BY METEOROLOGICAL RESEARCH FLIGHT AIRCRAFT

Date	Type	Pressure level	Did flight intersect frontal zone ?	Width of frontal zone	ΔT	Slope of front: Based on radio-sonde data	Slope of front: $\frac{\Delta z}{\Delta x}$	Slope of front: Direct observations
		mb		miles				
Nov. 3, 1950	cold	485	Yes	58	18	0·014	0·017	0·015
		550	Yes	79	16	0·014	0·010	
Apr. 27, 1951	cold	500	Yes	159	15	0·007	0·006	0·010
		650	Yes	195	14	0·012	0·008	
May 23, 1951	warm	500	Yes	187	8	0·016	0·017	0·020
		650	Yes	231	7	0·006	0·008	
June 12, 1951	cold	650	No	..	..	..	..	..
		850	No	..	..	..	..	..
June 13, 1951	warm	550	No	..	..	..	..	..
		650	Yes	107	8	0·006	0·014	..
June 26, 1951	warm	550	No	..	..	..	..	..
		650	No	..	..	..	..	..

APPENDIX—*continued*

Date	Type	Pressure level	Did flight intersect frontal zone	Width of frontal zone	ΔT	Slope of front: Based on radio-sonde data	Slope of front: $\frac{\Delta z}{\Delta x}$	Direct observations
		mb.		miles				
June 27, 1951	warm	Flight abandoned because of engine trouble						
July 9, 1951	warm	550	No	..	..	..	..	..
		700	Yes	99	5	0·004	0·004	..
Aug. 1, 1951	cold	500	Yes	55	4	0·024	0·024	0·032
		650	Yes	36	4	0·024	0·037	
Aug. 17, 1951	occlusion	650	No	..	..	..	..	..
		800	Yes	220	10	0·007	0·002	..
		850	No	..	..	..	..	..
Aug. 21, 1951	warm	650	No	..	..	..	..	..
		850	Yes	144	13	0·008	0·003	..
Aug. 23, 1951	warm	650	No	..	..	..	..	..
		850	Yes	62	4	0·002	0·006	..
Sept. 3, 1951	warm	600	Yes	86	4	0·012	0·012	0·006
		800	Yes	16	6	0·014	0·048	
Nov. 5, 1951	quasi-stationary	600	Yes	196	9	0·022	0·019	0·028
		850	Yes	199	13	0·013	0·019	
Nov. 14, 1951	warm	450	Yes	111	8	0·007	0·017	0·007
		550	Yes	46	4	0·010	0·047	
Dec. 11, 1951	warm	600	No	..	..	..	..	..
		700	No	..	..	..	..	..
Jan. 4, 1952	warm	700	Yes	110	8	0·005	0·013	0·006
		800	Yes	81	8	0·004	0·013	
Mar. 6, 1952	warm	650	Yes	212	10	0·006	0·007	..
		870	No	..	..	..	..	..
Mar. 7, 1952	warm	670	No	..	..	..	..	..
		870	Yes	149	7	0·006	0·010	..
Mar. 19, 1952	warm	710	Yes	93	6	0·020	0·027	0·008
		860	Yes	258	7	0·008	0·010	
Mar. 25, 1952	cold	500	No	..	..	..	..	..
		740	Yes	121	11	0·017	0·013	..
May 28, 1952	cold	560	Yes	179	14	..	..	..
		940	Yes	55	6	0·008	0·038	..
July 3, 1952	cold	500	Yes	173	12	0·013	0·011	0·050
		650	Yes	166	9	0·010	0·009	

(2440) Wt. 4675/BM/4407 K.5 10/55 Hw.